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Extending TDR Capability for Measuring Soil Density and Water Content for Field Condition Monitoring

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Abstract: Time domain reflectometry (TDR) can be used to measure the dry density of compacted soils, although it is believed that TDR could also be used to monitor the long-term performance of aging geotechnical assets. Understanding the deterioration of aging assets (earth dams, embankments) can be problematic; monitoring the relative condition with time may prove advantageous. In such applications, it would be likely that commercially available TDR probes and multiplexers would be used, and this paper illustrates that the current method does not perform particularly well with these. Therefore, an alternative method has been developed that, when applied to six fine-grained soils (exhibiting a range of plasticities), can deal with the impacts of multiplexers and commercial probes. It is shown that the dry density and gravimetric water content can be predicted with an accuracy of ±5 and ±2%, respectively. The accuracy can also be improved by correcting the TDR parameters for temperature. The new method is robust, relatively independent of the compactive effort and only marginally affected by the presence of multiplexers, making it suitable for field-monitoring applications. **DOI: 10.1061/(ASCE)GT.1943-5606.0001792.**

Introduction

Within many developed nations there are a large quantity of geotechnical assets (e.g., earth dams, flood levees, embankments and cuttings, and reinforced walls and pavements), many of which may have been constructed decades, if not a hundred or more years, ago. Soil is, by its very nature, a material that tends to form an equilibrium with the surrounding environmental and loading conditions; changes in these conditions can result in changes in the properties of the soil, which in turn can cause deterioration of the properties of the geotechnical asset. For example, changes in climatic and seasonal conditions (i.e., temperature and rainfall) can result in fine-grained soils (which exhibit plasticity) experiencing changes in volume due to the shrink/swell mechanism. Over a number of years, the soil may experience, for example, nonuniform vertical and horizontal movements, changes in fabric structure, changes in physical properties (water content and shear strength parameters), which can result in deterioration of the geotechnical properties of the geotechnical asset (i.e., weakening of a slope resulting in slippage). The deterioration of geotechnical assets can be related, in part, to change in water content with time (Pritchard et al. 2014; Gunn et al. 2015). The water content is an important parameter when considering the behavior of soils due to a number of factors including changes in the three-phase model for the soil, potential changes in volume, changes in the pore water pressure regime leading to changes in effective stress, and hence changes in shear strength. Numerous methods have been developed for measuring the soil water content in the field. Among these, electromagnetic techniques are the most commonly used due to their accuracy, versatility, and lack of radiation hazard compared to other methods (Topp 2003). Replacement of aging geotechnical assets can be prohibitively expensive, hence monitoring and maintenance (when required) is often the preferred option. Traditional monitoring methods (invasive or noninvasive) tend to be discrete in nature (such as installation and surveying of boreholes or use of surface/borehole geophysical techniques), whereas the installation (either during construction of the geotechnical structure or retrofitted) of relatively inexpensive sensors that permit continuous monitoring could offer an attractive alternative when attempting to determine the relative condition of a potentially vulnerable asset. Time domain reflectometry (TDR) has been used to monitor water content in soils for many years, and more recently, a method was developed to investigate the dry density and water content of compacted soils (ASTM-D6780/D6780M).

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Possibility of Using TDR in Geotechnical Asset Condition Monitoring

TDR has been extensively, and successfully, used in the past both in the laboratory and in the field for assessment of water content of the soil [see Noborio (2001), Jones et al. (2002), and Robinson et al. (2003) for an in-depth overview of the TDR technique]. In summary, TDR sends a broadband electromagnetic (EM) pulse in the frequency range between a few MHz and approximately 1 GHz (Friel and Or 1999) across a coaxial transmission line comprising a coaxial cable and a probe. A TDR probe usually consists

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of an inner metal rod carrying the signal surrounded by one or more outer rods that contain the EM field (Zegelin et al. 1989). Reflections occur whenever there is a change in the EM properties of the material within the sampling volume of the probe and when the cross-sectional geometry of the inner and outer conductors changes (Clarkson et al. 1977; Yanuka et al. 1988; Feng et al. 1999; Lin 2003; Lin and Tang 2007). TDR measures the amplitude and the time of these reflections. The travel time between the reflections occurring at the start and at the end of the TDR probe is related to the complex relative dielectric permittivity of the medium (hereafter the terms relative and dielectric will be omitted for simplicity), and can be used to measure an apparent permittivity, K_a, defined by Eq. (1) (Topp et al. 1980)

$$\boldsymbol{K_a} = \frac{\boldsymbol{\varepsilon_r'(f)\mu_r}}{2}\left(1+\sqrt{1+\left(\frac{\boldsymbol{\varepsilon_p''(f)}+\frac{\sigma_{dc}}{2\pi f\varepsilon_0}}{\boldsymbol{\varepsilon_r'(f)}}\right)^2}\right) \quad (1)$$

where $\varepsilon_r'(f)$ = frequency dependent real permittivity representing the storage of energy through separation of charges; μ_r = relative magnetic permeability; $\varepsilon_p''(f)$ = frequency dependent imaginary permittivity representing the relaxation losses; σ_{dc} = static electrical conductivity (S/m); f = frequency of the signal (Hz); and ε_0 = absolute permittivity of free space (8.854×10^{-12} F/m). Water has a significantly larger permittivity than the other soil constituents (i.e., solid particles and air); therefore, TDR measurements of soil can be used as a proxy for measuring the soil water content (Topp et al. 1980). Many empirical (e.g., Topp et al. 1980; Ledieu et al. 1986; Malicki et al. 1996; Jacobsen and Schjønning 1993; Wensink 1993; Siddiqui and Drnevich 1995; Curtis 2001) and physically based (e.g., Birchak et al. 1974; Dobson et al. 1985; Roth et al. 1990) relationships linking the TDR measured K_a to the soil water content have been described in the literature. However, due to the heterogeneous nature of soils, a universal relationship has not been found that can produce accurate results for every soil. For projects where accuracy is of primary importance, it is therefore still advisable to perform a soil-specific calibration (Thring et al. 2014). TDR has also been shown capable of measuring the low frequency bulk electrical conductivity (BEC, S/m) from the attenuation of the signal after reaching a steady-state level (Giese and Tiemann 1975; Topp et al. 2000). Given that TDR measures a volume of soil, it is used to measure the soil volumetric water content. The soil water content, often also called soil moisture, can be defined either as volumetric water content θ [Eq. (2a)] or as gravimetric water content, w [Eq. (2b)], both usually expressed as percentage by volume and by mass, respectively. The use of one or the other term varies across the disciplines but should always be specified to avoid confusion. In geotechnical engineering, the use of w is preferred because it can be easily and accurately measured in the laboratory using the oven-drying method (BSI 1999b) and can be directly linked to the mechanical behavior of the soil. The volumetric and gravimetric water contents are linked through Eq. (2c)

$$\boldsymbol{\theta} = \frac{\boldsymbol{V_w}}{\boldsymbol{V_t}} \quad (2a)$$

$$\boldsymbol{w} = \frac{\boldsymbol{m_w}}{\boldsymbol{m_s}} \quad (2b)$$

$$\boldsymbol{\theta} = \boldsymbol{w}\frac{\boldsymbol{\rho_d}}{\boldsymbol{\rho_w}} \quad (2c)$$

where V_w = volume occupied by the water (m^3); V_t = total volume of soil investigated (m^3); m_w = mass of water (g); m_s = mass of soil contained in the investigated sample (g); ρ_d = soil dry density, defined as the ratio between m_s and V_t (Mg/m^3); and ρ_w = density of the water (Mg/m^3). More recently, TDR was shown capable of measuring the soil ρ_d and w and therefore making it more appealing to geotechnical engineers. Thring et al. (2014) proposed simple methods for converting θ to w by using the information contained in the soil description and other available soil data. Although quick and inexpensive, these methods only provide estimates of these parameters and are unlikely to be as accurate as direct measurements. Siddiqui and Drnevich (1995) proposed a method for measuring both ρ_d and w in the field by taking two separate TDR measurements, one in the soil in situ and one in a sample of the soil that has been excavated and compacted in a mold of known volume (for which the soil bulk density could be determined directly on site using a balance). This results in two water content values and one bulk density being obtained; assuming no water loss during the procedure, the method uses the two separate measurements to determine the ρ_d and w of the in situ soil. The method was validated by other studies (Lin et al. 2000; Siddiqui et al. 2000) and led to the creation of the ASTM-D6780 standard (ASTM 2003). An improved method was subsequently developed (Yu and Drnevich 2004; Drnevich et al. 2005) that avoided the need for two separate field measurements and did not require the excavation of the soil sample, reducing testing time and effort. For this reason the method has become known as the one-step method and was included in an updated version of the ASTM-D6780 standard (Procedure B, ASTM 2005). This method involves the measurement of K_a and BEC by TDR. As both are related to w, if normalized by ρ_d, they can be used together to determine these parameters following a soil-specific laboratory calibration. The procedure includes a temperature correction, if testing outside the normal room temperature range, and an adjustment of BEC to account for the fact that the pore fluid conductivity of the soil in the field is generally different from the pore fluid conductivity obtained in the laboratory. Despite the one-step method proposed by Yu and Drnevich (2004) typically producing satisfactory results, it has been found to be sensitive to the compactive effort and dependent on the adjustment for BEC, making it potentially less accurate when applied in the field. Independent studies reported satisfactory results in the laboratory but unsatisfactory results in the field that have been attributed to soil disturbance during probe insertion and to theoretical flaws in the adjustment for BEC (Lin et al. 2012). Hence, the method was improved by Jung et al. (2013a, b), who introduced a new type of calibration relationship that was shown to be relatively independent of the compactive effort and produced better accuracy. This method forms the current ASTM-D6780/D6780M (ASTM 2012) standard and is described in more detail in the next section. The main issue with ASTM-D6780/D6780M is that it requires a specific type of TDR probe. If the use of TDR is to be expanded into geotechnical asset monitoring, then it would be much better if it could be used with off-the-shelf probes that are more suitable for burial (three-rod TDR probes can be buried and the surrounding soil more easily compacted). Multiplexers are also necessary in field monitoring applications as multiple TDR probes are likely to be required to monitor a relatively large zone of soil, and these must be connected to the TDR (it would be prohibitively expensive to pair one TDR per probe buried on site). Therefore, the aim of this study was to evaluate the ASTM-D6780/D6780M method using commercially available (and comparatively inexpensive) three-rod TDR probes, with and without the addition of two levels of multiplexers, thus making it much more attractive for long-term field monitoring. It was found that the method was less than ideal in this experimental setup, and an improved method has been developed. This could open up a major avenue of exploitation for the TDR technique, including the long-term condition monitoring of geotechnical assets, such as dams, embankments and other earth structures.

Background on the Current Calibration for Measuring ρ_d and w

The basis for the current calibration procedure reported in the ASTM-D6780/D6780M standard (ASTM 2012) has been described in detail by Jung et al. (2013a, b). As K_a is directly related to θ and the conversion factor between w and θ is the density term ρ_d/ρ_w [Eq. (2c)], it is appropriate to express the relationship between K_a and w with Eq. (3) (Siddiqui and Drnevich 1995; Siddiqui et al. 2000; Yu and Drnevich 2004; Drnevich et al. 2005). It should be noted that the subscript 1 has been added to the calibration coefficients (i.e., a_1 and b_1) to indicate the first step of the calibration procedure

$$\sqrt{K_a}\frac{\rho_w}{\rho_d} = a_1 + b_1 \times w \tag{3}$$

A number of authors have demonstrated that the inclusion of a density term improves the relationship between K_a and θ, indicating that this relationship is also affected by the soil density (Ledieu et al. 1986; Roth et al. 1992; Dirksen and Dasberg 1993; Jacobsen and Schjønning 1993; Malicki et al. 1996; Gong et al. 2003; Thring et al. 2014). For this reason, Eq. (3) is thought to be superior compared to other empirical equations relating K_a (or $\sqrt{K_a}$) directly to θ (Siddiqui and Drnevich 1995; Siddiqui et al. 2000; Drnevich et al. 2005). However, to calculate w and θ, a value of ρ_d is required. Hence, Jung et al. (2013a) proposed an independent relationship relating a voltage and density normalization term to the K_a measured by TDR and expressed by Eq. (4) (it should be noted that the subscript 1 on the coefficients (i.e., c_1, d_1, and f_1) has been kept the same as in Jung et al. (2013a) for consistency reasons, although this forms the second step of the calibration procedure)

$$V_r\frac{\rho_w}{\rho_d} = c_1 + d_1(K_a - 1) - c_1 \times e^{-f_1(K_a-1)} \tag{4}$$

where V_r = ratio between the first voltage drop, V_1, occurring between the start and the end of the probe [Fig. 1(a)], and the final steady-state voltage level V_f obtained after all the multiple reflections have attenuated [Fig. 1(b)]. By re-arranging Eq. (4) and using the calibrated coefficients c_1, d_1, f_1, the soil ρ_d can be calculated and used in Eq. (3) together with the calibrated coefficients a_1 and b_1 to find w. θ can also be calculated from Eq. (2c). Eqs. (3) and (4) form the first and second step of the calibration procedure proposed by Jung et al. (2013a) and are incorporated in the ASTM-D6780/D6780M standard (ASTM 2012). The methodology was tested on a number of ASTM reference soils and was demonstrated to be a significant improvement over the previous methods developed for the calculation of ρ_d and w with TDR. To the knowledge of the authors, this method was only tested using a specifically developed probe, also referred to as multiple rod probe (MRP), originally introduced by Siddiqui and Drnevich (1995) and further described by Siddiqui et al. (2000). This probe design, featuring a detachable head, is well suited to in situ field measurements where repeated insertions and withdrawals are required and has the advantage that it simulates well a coaxial transmission line having one central rod surrounded by three external rods (Zegelin et al. 1989). The MRP was on the market for a limited number of years, but at the present time it cannot be purchased commercially. However, although it can easily be built in a workshop, it would be preferable to be able to use off-the-shelf probes to enable more widespread use of the method. In addition, the application of the calibration procedure using common and inexpensive three-rod TDR probes could potentially extend its applicability to field monitoring (i.e., measurements being taken over a period of time). In fact, probes with two or three parallel rods and with a nondetachable head are more suited to continuous monitoring in the field and have been used extensively by a number of authors (Herkelrath et al. 1991; Delin and Herkelrath 2005; Rajkai and Ryden 1992; Bittelli et al. 2008; Curioni et al. 2017).

Materials and Methods

Soil Types

A range of soil types, all fine-grained soils, were selected for this study. Five of these soils were prepared using different proportions of English China clay, Na-bentonite and kiln dry sand (<425 μm) so that they would be classified differently according to the Casagrande plasticity chart (Casagrande 1932), and therefore covering a range of physical behaviors (Fig. 2). In addition, one natural soil was collected from the field at Blagdon, located in the southwest of the United Kingdom. Table 1 shows the characterization parameters for each soil.

Experimental Procedure

The laboratory prepared soils were initially mixed dry to ensure the individual components were mixed homogeneously and later distilled water was added to achieve specific water conditions. The samples were sealed in plastic bags and left to equilibrate for a minimum period of 24 h. In the case of the natural soil

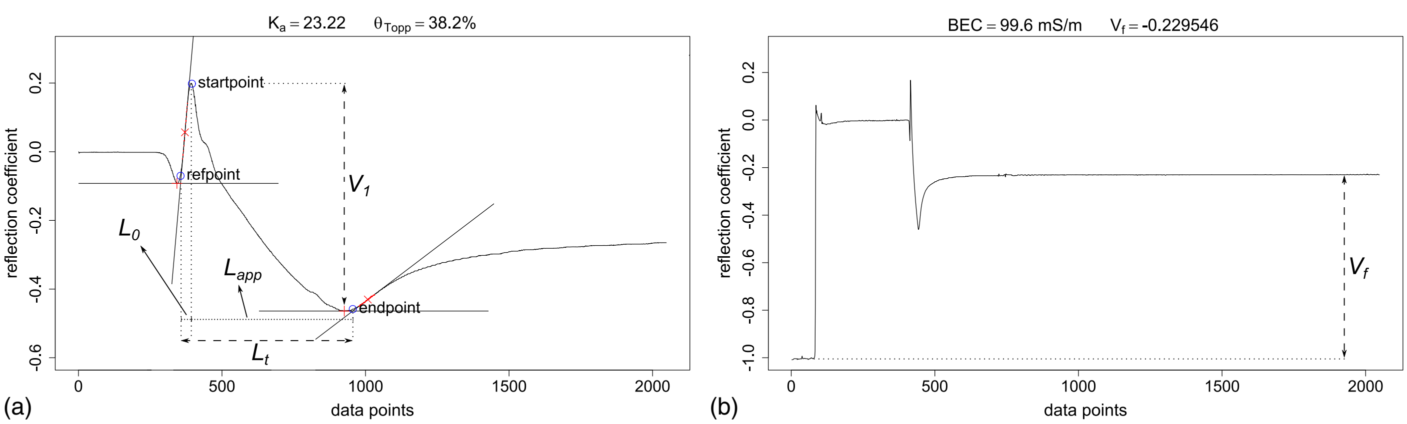

Fig. 1. Example of TDR waveforms in soil with the list of parameters used in the analysis: (a) is used for measuring K_a and V_1; (b) is used for measuring BEC and V_f

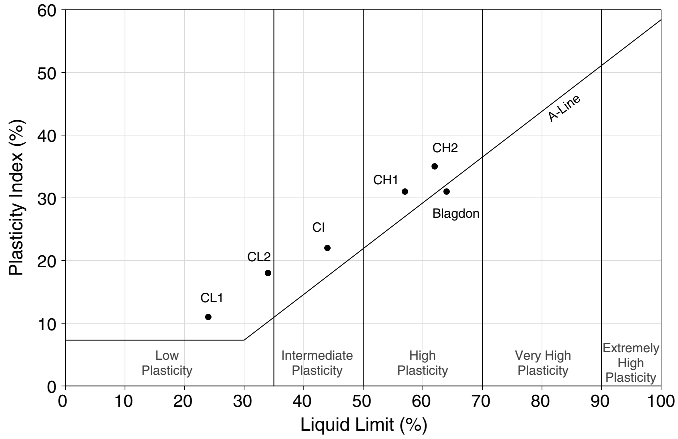

Fig. 2. Position of the soils studied on the plasticity chart

Table 1. Characterization Properties of the Soils Studied

Parameter	CL1	CL2	CI	CH1	CH2	Blagdon
Sand (%)	70	50	30	10	0	48
English China clay (%)	28.5	47.5	66.5	85	95	N/A
Na-bentonite (%)	1.5	2.5	3.5	5	5	N/A
Sand >425 μm (%)	0	0	0	0	0	23
Sand <425 μm (%)	70	50	30	10	0	25
Silt (%)	0	0	0	0	0	37
Clay (%)	30	50	70	90	100	15
Plasticity classification[a]	CL	CL	CI	CH	CH	MH
Plastic limit (%)	13	16	22	26	27	33
Liquid limit (%)	24	34	44	57	62	64
Plasticity index (%)	11	18	22	31	35	31
Linear shrinkage (%)	2	8	6	9	9	14

[a]In the plasticity classification C = clay; M = silt; L = low; I = intermediate; H = high.

(Blagdon), the samples were air-dried and water added to achieve the required water contents. The compaction procedure followed the BS 1377-4 standard (BSI 1999a). However, a larger mold (102 mm diameter, 203 mm height, 1,658.77 cm^3 volume) shown in Figs. 3(a and b) was used to be able to insert the 150-mm-long TDR probes used in this study [Fig. 3(c)]. To achieve a standard compactive effort [BSI 1377-4 (BSI 1999a)], the soil was compacted in five layers using a 2.5-kg rammer with a drop height of 300 mm using 27 blows for each layer. Some extra samples were also prepared using a reduced and an increased compactive effort (compared to the standard compaction) to investigate the effect of compactive effort on the results. The lighter compacted samples were prepared using the same rammer as the standard compaction, but the number of blows was reduced to 16. The more heavily compacted samples were prepared in eight layers and compacted using a 4.5-kg rammer with a drop length of 450 mm and 28 blows for each layer. To reduce the influence of experimental errors, two tests were conducted at each water content value. Once the sample was compacted, a TDR probe was inserted vertically centrally into the sample after predrilling holes to facilitate insertion. For the stiffer samples, typically at very low water contents, it was necessary to clamp the probe head and move the whole mold upward on to the probe to force it into the soil until it was fully inserted [Fig. 3(b)]. The temperature was taken with a RTD thermometer manufactured by S.Brannan and Sons, with an accuracy of ±0.4°C [Fig. 3(d)]. TDR readings were taken in repetitions of five after removing the metal base from the mold. This was a precaution to remove potential edge effects of the metal mold on the TDR measurements. However, previous studies (Zegelin et al. 1989; Ferré et al. 1998; Nissen et al. 2003) indicated that the sampling volume of conventional three-rod probes is mostly contained within the space between the inner and outer conductors. The probe was placed at a distance of approximately 50 mm from the metal mold, and therefore, the sampling volume was well inside its borders. Preliminary tests with and without the metal base confirmed that there were no apparent differences in the TDR results. After taking the TDR readings, the sample was removed from the mold, and three subsamples were taken from the top, middle, and bottom corresponding to the location of the TDR probe and the gravimetric water contents, w, determined (BSI 1999b). Separate validation tests were performed to study the effect of compactive effort and temperature. For each soil, a sample was prepared using a lighter compaction (LC), standard compaction (SC), and heavy compaction (HC) procedure, as described above, near to the optimum water content (i.e., the water content corresponding to the maximum dry density achieved during the sample preparation) obtained with the standard compaction procedure. These samples were wrapped in cling film to reduce evaporation and placed in a sealed incubator where the temperature was varied between 5 and 25°C in steps of approximately 5°C. The procedure of taking measurements using the TDR probe was otherwise the same as described above. Finally, an independent experiment on the CI mixture (an intermediate plasticity soil mixture according to Fig. 2) was conducted by burying a TDR probe horizontally in a large cylinder (250-mm internal diameter). To simulate site compaction, the soil was compacted in layers between 30 and 60 mm in thickness (after compaction) using a Kango vibratory hammer with a rubber attachment over a circular plate across the full diameter of the cylinder. The test was repeated for a range of water contents, from 14 to 21%.

TDR Setup and Analysis

The TDR equipment used in this study consisted of a TDR100, SDMX50 50 Ω multiplexers, common three-rod TDR probes (model CS635, 150-mm long with either a 5-m or 6-m LMR200 low-loss cable) manufactured by Campbell Scientific. The TDR probes were calibrated individually for both K_a in air, acetone, and water, and *BEC* in potassium chloride solutions, following procedures extensively described in the literature (Heimovaara 1993; Robinson et al. 2003; Lin et al. 2007, 2008; Huisman et al. 2008; Bechtold et al. 2010; Curioni et al. 2012). A separate calibration was conducted for the two different arrangements used, i.e., without multiplexers (mux0) and with two levels of multiplexers (mux2), since it is known that adding attachments can affect the TDR output (Logsdon 2006; Curioni et al. 2012). It was decided to conduct the analysis with two levels of multiplexers because with this setup up to 64 TDR probes can be connected to the same TDR unit, and this would cover the majority of field-monitoring applications. It is worth pointing out that although the *BEC* values were calculated in this study only the values of V_f were actually used to determine ρ_d and w. In projects where *BEC* values are not needed, this could save significant time in the equipment setup since the calibration for *BEC* is time consuming. TDR waveforms were collected either with an in-house *MATLAB* program or with the *PCTDR* software using the following settings: velocity propagation factor = 1; number of averages = 20; number of points = 2,048; start and length optimized to show the interesting portion of the waveform, typically 7.6 and 2.6 m without multiplexers and 9.6 and 2.6 m with two levels of multiplexers, respectively. For measuring V_f and *BEC* the values of 0 and 500 m were used as the start and the length, respectively. The analysis of the waveforms was carried out with

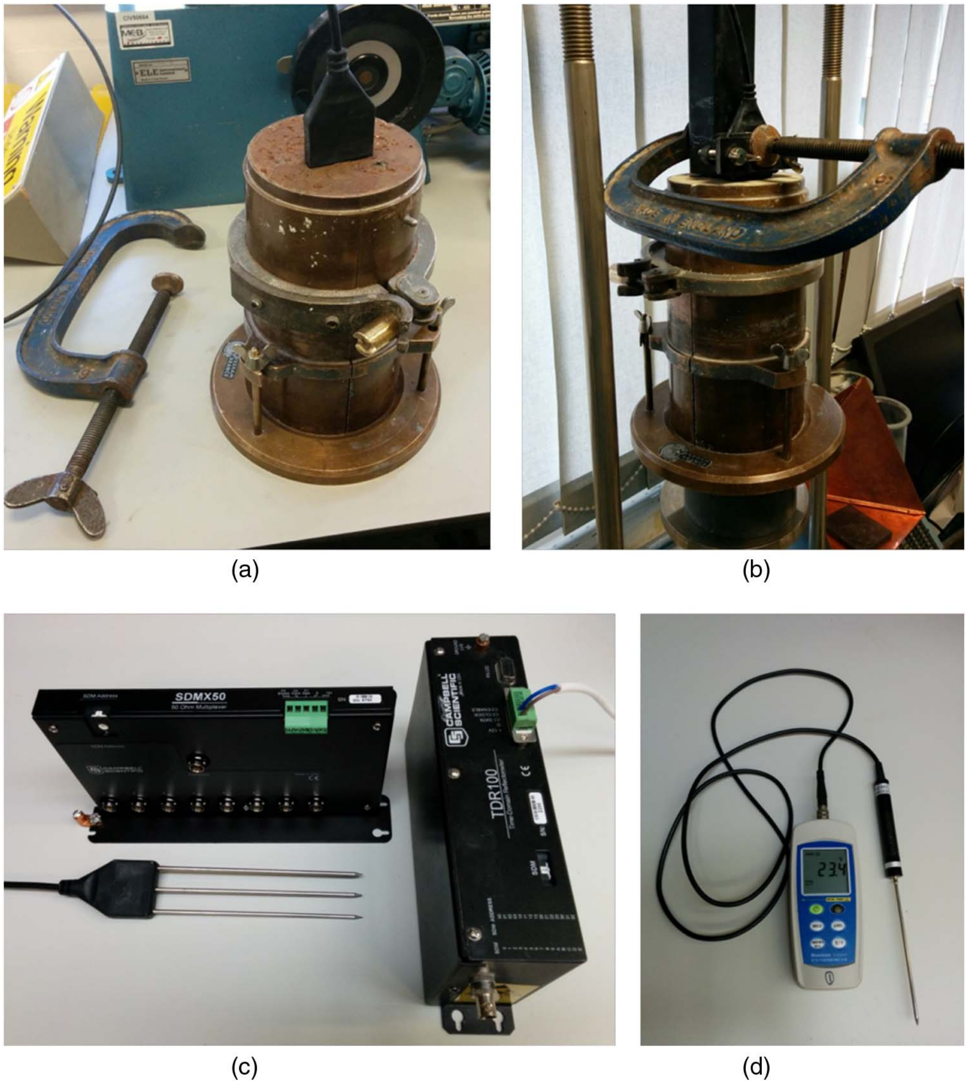

Fig. 3. (a) TDR probe inserted in a compaction mold; (b) clamp used to facilitate probe insertion in stiffer soils; (c) TDR equipment; (d) temperature sensor

scripts developed using the open-source software *R* (copies can be provided on request). The analysis is very similar to the one reported in Curioni et al. (2012). The script used to calculate K_a finds the minima and the inflection points occurring in the head of this type of probe and near the reflection at the end of the probe, and intersects the corresponding tangent lines as shown in Fig. 1(a) to find a reference and an end point. The probe offset, L_0 (m), corresponding to the distance from the reference point in the probe head and the actual start of the probe [Fig. 1(a)], and the calibrated length of the probe, L_{cal} (m), were calculated from Eq. (5) after calibration in media with known values of K_a

$$L_t = L_0 + L_{\mathrm{cal}}\sqrt{K_a} \tag{5}$$

where L_t (m) = distance between the reference point and the end point [Fig. 1(a)]. L_0 was added to find the real start point and the distance between this point and the end point, L_{app} [m, Fig. 1(a)], was used to calculate K_a using Eq. (6)

$$K_a = \left(\frac{L_{\mathrm{app}}}{L_{\mathrm{cal}}}\right)^2 \tag{6}$$

In this study, distilled water, acetone and shorted measurements in air were used during calibration. These mediums are well suited to calibration since they are nondispersive and have negligible imaginary components over the TDR frequency range, both necessary requirements for relating their reference real permittivity to the apparent permittivity measured by TDR. L_0 and L_{cal} are assumed constant, but in reality vary slightly with the material used to calibrate the probes. In this study, the values of L_0 and L_{cal} obtained from calibration in water and acetone were selected since they were more consistent with the expected values reported by the manufacturer and independent tests in water produced slightly more accurate results than using shorted measurements in air for calibration. This could be due to the difficulty of physically shorting the probes and to the higher uncertainty in the analysis of the waveforms in air. The values of V_1 and V_f used to calculate ρ_d and w were also extracted by the script. In this study, two values of V_1 were calculated. One value was calculated from the peak at the start of the probe and the minimum located to the left of the end reflection, and one value was calculated using the difference in reflection coefficient between the calculated start point and end point. The second value was found to provide slightly more accurate results and was therefore used. V_f was taken from the average voltage value of the last 100 points in the waveform used for measuring *BEC* [Fig. 1(b)]. As mentioned earlier, five repetitions were taken for each sample to reduce the uncertainty associated with the identification of the start and end reflection points, and the mean values of K_a, V_1, and V_f were used in the analysis.

New Step 2 Calibration Relationship

The original aim of this study was to test the recently proposed calibration method by Jung et al. (2013a) (i.e., ASTM-D6780/D6780M) using conventional and inexpensive three-rod TDR probes together with multiplexers, which would make the method applicable to continuous field monitoring. However, it was found that this method did not always produce reliable results and was affected by the addition of multiplexers due to the suboptimal performance of the second step of the calibration. Hence, a number of new empirical relationships were tested, and a modification of the current relationship was found to be more suitable for the calibration of ρ_d. Fig. 4 shows the steps necessary for developing a soil-specific calibration with TDR. Fig. 4(a) shows the standard compaction curves for the soils studied, indicating the wide range of conditions tested. Using the combination of the measured ρ_d and w an empirical calibration against w (Step 1) was developed for each soil according to Eq. (3). These results showed some scatter, indicating slightly different relationships depending on the soil type, and demonstrate the need for soil-specific calibrations to obtain better accuracy. In addition, the scatter increased marginally with two levels of multiplexers (mux2) due to the higher uncertainty in the determination of K_a. In general, the results from this first step of the calibration were satisfactory, and because Eq. (3) has a theoretical foundation (Siddiqui and Drnevich 1995; Siddiqui et al. 2000; Drnevich et al. 2005), it was not modified in this study. Fig. 4(c) shows the relationship between the voltage and density normalization parameter suggested by Jung et al. (2013a) versus K_a. As for Step 1, each soil showed a unique relationship, but significant scattering was present that yielded inaccurate predictions of ρ_d and subsequently w. The effect of multiplexers is also evident in the results. Both K_a and the voltage ratio V_r were affected by the increased attenuation caused by the use of two levels of multiplexers and therefore produced less accurate results. As mentioned earlier, it was thought that a better relationship with improved precision and accuracy could be developed, which would also reduce the influence of multiplexers. A number of alternative empirical relationships were tested, and the proposed one is expressed by Eq. (7) and shown in Fig. 4(d)

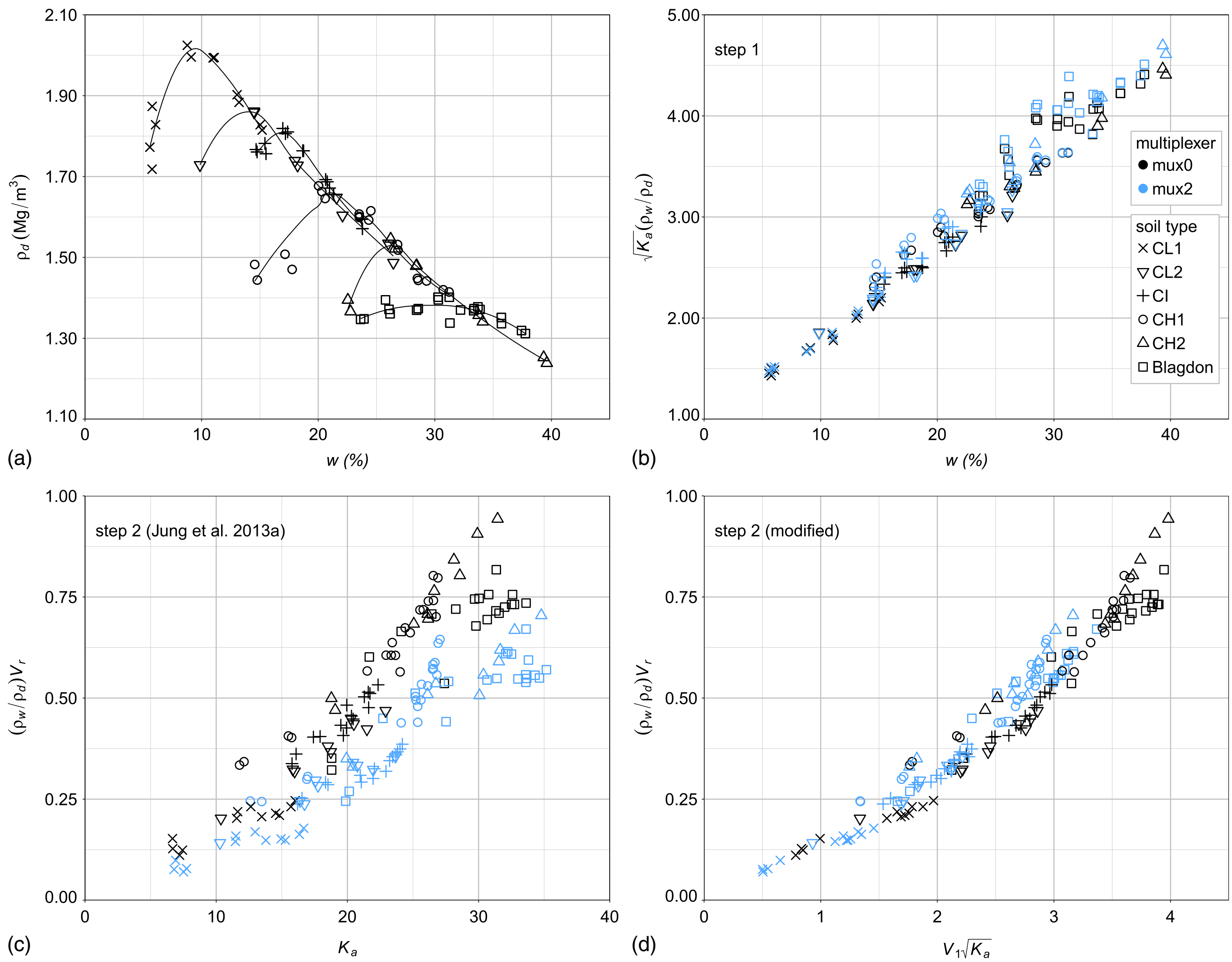

Fig. 4. Soil-specific calibration procedure for the soils studied: (a) compaction curves with standard compaction according to BSI (1999a); (b) Step 1 of the calibration; (c) currently accepted calibration relationship used in Step 2; (d) new proposed relationship for Step 2

$$V_r \frac{\rho_w}{\rho_d} = a_2 + b_2 (V_1 \sqrt{K_a})^{c_2} \quad (7)$$

where a_2, b_2, and c_2 = calibration coefficients (the subscript 2 was used to indicate the second step of the calibration procedure). Similar to Eq. (4), this relationship makes use of the density and voltage normalization factor and relates it to a quantity consisting of a combination of both K_a and V_1 measured by TDR. Although this form was obtained empirically, it is justified by the fact that both V_1 and K_a are affected by changes in ρ_d. The use of the squared root of K_a and V_1 was found to improve the accuracy of the relationship. Previous authors showed that V_1 increases with increasing ρ_d while keeping w constant (Yu and Drnevich 2004; Jung et al. 2013a) and improved calibrations between θ and K_a (or between θ and $\sqrt{K_a}$) have been reported by several authors (e.g., Ledieu et al. 1986; Dirksen and Dasberg 1993; Jacobsen and Schjønning 1993; Malicki et al. 1996; Thring et al. 2014), demonstrating that K_a is indeed affected by ρ_d. For a given w, K_a is expected to increase slightly with increasing ρ_d due to the reduced volume occupied by air (Gong et al. 2003). Similar to Jung et al. (2013a), a physical constraint (i.e., $V_1 = 0$ in air) was added to the model and was found to further improve the results. Therefore, the relationship was simplified by setting the coefficient a_2 equal to zero. The remaining coefficients b_2 and c_2 were obtained by minimizing the sum of squares of the differences between measured and calculated values using Eq. (7). Table 2 shows the calibrated coefficients for the soils studied using Eqs. (3), (4), and (7). Due to the limited nature of the data sets involved, the proposed equation was derived empirically, rather than probabilistically, although simple statistical approaches (such as curve fitting using R^2 values) were used. It is noted that an empirical approach was previously successfully used when developing ASTM-D6780/D6780M [i.e., Eq. (4)] and is commonly used when deriving relationships that apply to the behavior of soils. The proposed equation was selected because it yielded robust results (based on R^2 values and performance during cross-validation) and due to its simplicity; it only requires two unknown coefficients, b_2 and c_2, after constraining a_2 to zero. The number of unknown coefficients and the curvature of this equation were small compared to other models, and this made the method more robust and less dependent on the number of data points used to develop it. This is a clear practical advantage over other models. Fig. 5 shows the second step of the calibration relationship for all the soils from the current data set using the Jung et al. (2013a) method [Eq. (4)] and the new modified relationship [Eq. (7)]. Eq. (7) demonstrated an improvement compared to Eq. (4), with a reduced effect due to multiplexers and a better fit to the data. As will be discussed later, it was also found that Eq. (7) was more robust and less dependent on the number of data points used for the calibration than Eq. (4). By re-arranging Eq. (7), ρ_d can be calculated using Eq. (8)

$$\rho_d = \frac{\rho_w V_r}{a_2 + b_2 (V_1 \sqrt{K_a})^{c_2}} \quad (8)$$

Once the ρ_d measured by TDR is known, w can be obtained by rearranging Eq. (3) into Eq. (9)

$$w = \frac{1}{b_1} \times \left(\sqrt{K_a} \frac{\rho_w}{\rho_d} - a_1 \right) \quad (9)$$

Results and Discussion

Effect of Multiplexers on the TDR Parameters

Multiplexers are necessary for field-monitoring applications since they allow multiple probes to be connected to the same TDR unit. Currently, the addition of one SDMX50 multiplexer allows up to eight TDR probes to be connected to the same TDR unit. Two levels of multiplexers allow the connection of up to 64 probes and, therefore, can be used in complex field layouts. It is well known that the addition of multiplexer introduces noise to the signals, causes attenuation, and rounds the reflections making it more difficult to identify them accurately (Logsdon 2006; Curioni et al. 2012). Fig. 6 shows waveforms taken on two separate soils at a range of water contents and dry densities, with and without multiplexers. It is clear that V_1 was significantly reduced by the addition of multiplexers. Fig. 7 shows the effect of multiplexers on the TDR parameters used in Eqs. (4) and (7). V_r and the new parameter $V_1\sqrt{K_a}$ were strongly reduced when using multiplexers, but the magnitude of the reduction was similar for the two parameters. K_a was generally overestimated when using multiplexers due to the difficulty of identifying the probe's end reflection on rounded waveforms (Fig. 6). The effect of incorporating multiplexers on the two methods is illustrated in Fig. 4. In the original method, the impact of the inclusion of multiplexers is clearly apparent [Fig. 4(c)] as the decrease in V_r and increase in K_a with the addition of multiplexers resulted in a change in the $(\rho_w/\rho_d)V_r$ versus K_a relationship; the modified relationship was less affected by multiplexers because both V_r and $V_1\sqrt{K_a}$ decreased in a similar way when adding multiplexers [Fig. 4(d)]. It is important to note that the effect of long cable lengths was not investigated in this study, although it is expected that long cables would have similar effects to the addition of multiplexers, with increased attenuation, reduced V_1 and

Table 2. Soil-Specific Calibration Coefficients Calculated without Multiplexers (mux0) and with Two Levels of Multiplexers (mux2)

	Step 1 [Eq. (3)]		Step 2 [Eq. (4)]			Step 2 [Eq. (7)]		
Soil type	a_1	b_1	c_1	d_1	f_1	a_2	b_2	c_2
CL1_mux0	0.9761	0.0801	0.6303	−0.0083	0.0576	0.0000	0.1409	0.7858
CL2_mux0	1.0216	0.0798	−0.0917	0.0255	0.0441	0.0000	0.1274	1.2396
CI_mux0	1.0749	0.0793	0.0399	0.0232	−0.0001	0.0000	0.1125	1.3585
CH1_mux0	1.2041	0.0786	−0.0604	0.0302	0.0720	0.0000	0.1571	1.1818
CH2_mux0	1.2490	0.0786	−0.1687	0.0364	0.2149	0.0000	0.1354	1.3715
Blagdon_mux0	1.4722	0.0772	−0.0123	0.0245	0.0714	0.0000	0.1412	1.2309
CL1_mux2	0.9981	0.0800	0.6874	−0.0091	0.0407	0.0000	0.1289	0.8208
CL2_mux2	1.0296	0.0798	0.2142	0.0144	0.0176	0.0000	0.1390	1.1950
CI_mux2	1.1761	0.0787	0.0126	0.0153	0.0937	0.0000	0.1372	1.1557
CH1_mux2	1.2963	0.0775	−0.7566	0.0377	0.0301	0.0000	0.1565	1.1978
CH2_mux2	1.4046	0.0781	−0.0659	0.0231	0.5250	0.0000	0.1594	1.2489
Blagdon_mux2	1.5692	0.0767	−0.0045	0.0180	0.1275	0.0000	0.1487	1.2005

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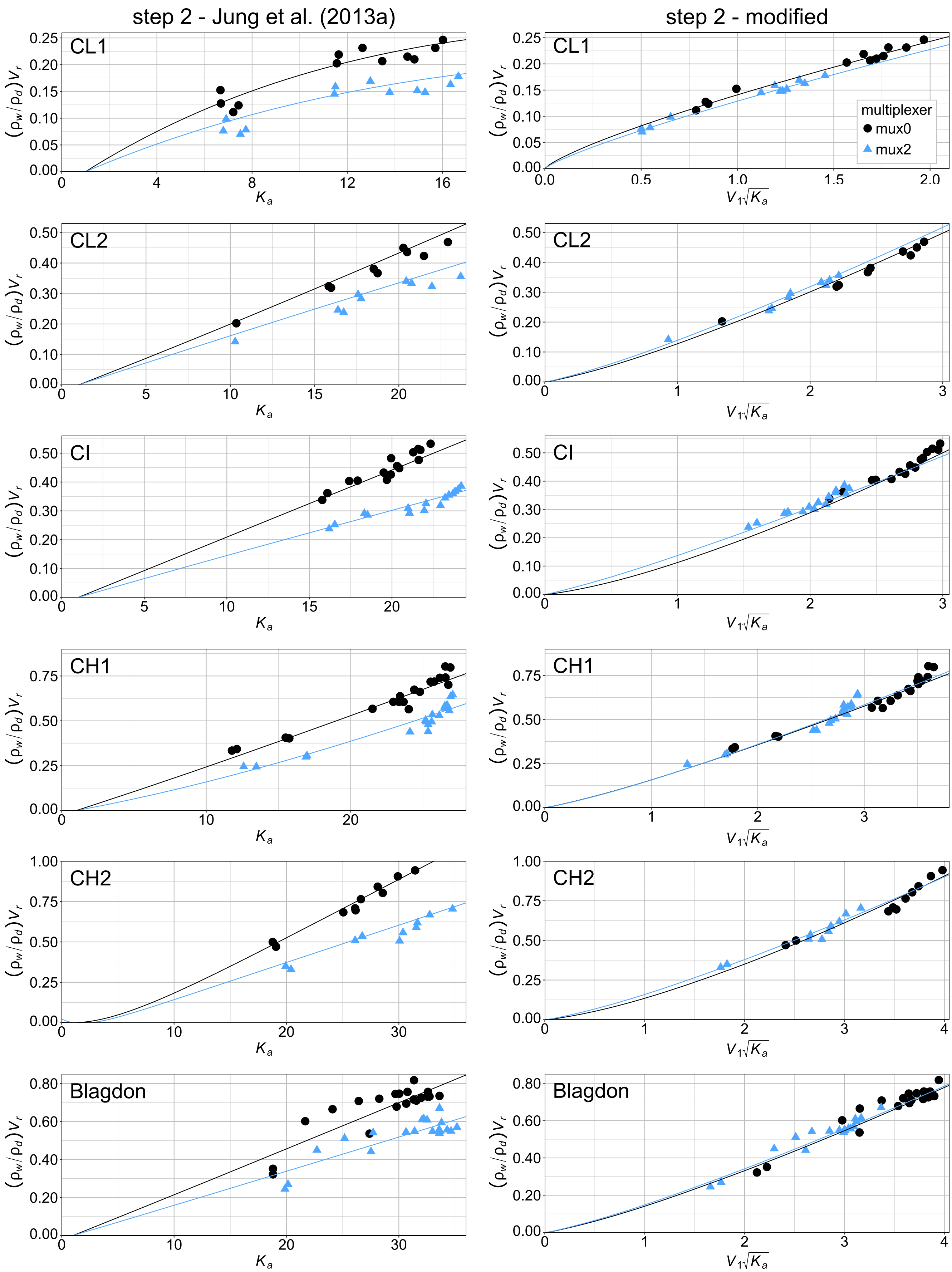

Fig. 5. Comparison between the Jung et al. (2013a) relationship used in Step 2 and the proposed new relationship for all the soils tested in this study

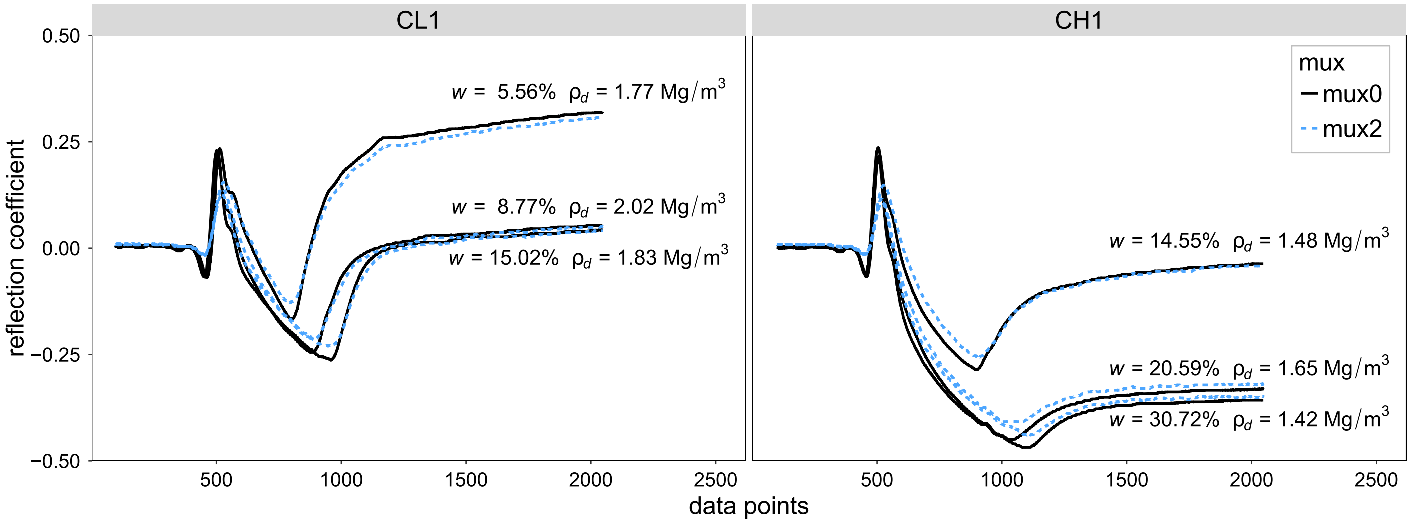

Fig. 6. TDR waveforms taken at a range of w and ρ_d for two separate soils with (mux2) and without (mux0) multiplexers

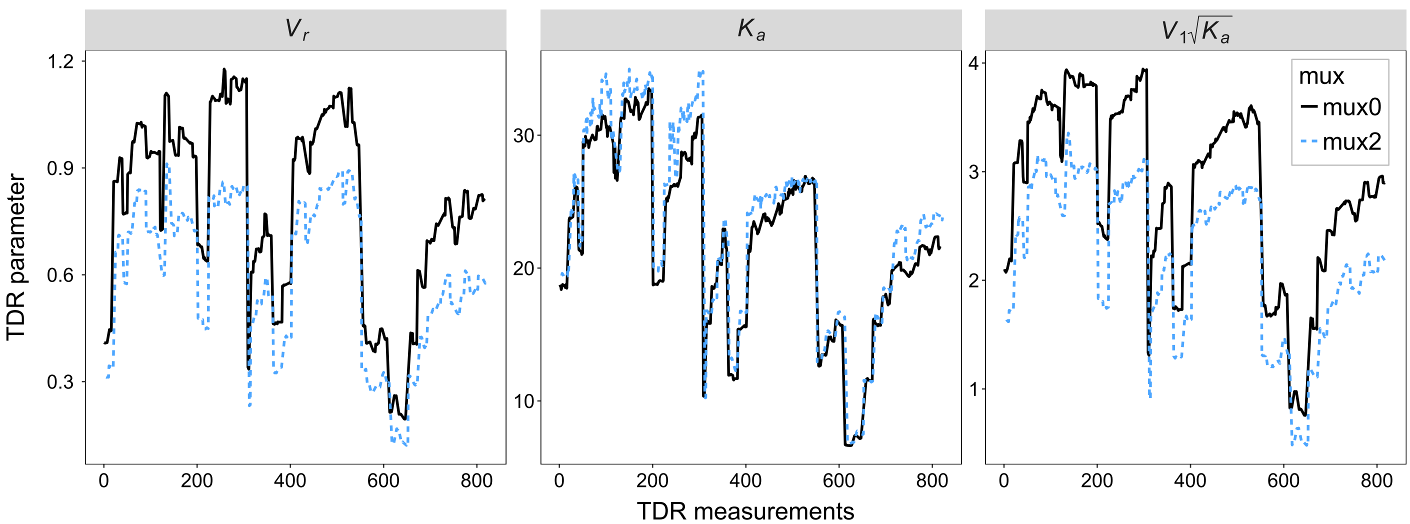

Fig. 7. Variation of V_r, K_a, and $V_1\sqrt{K_a}$ for all the TDR measurements taken in the different soils with (mux2) and without (mux0) multiplexers

rounding of the waveforms (Logsdon 2006). For these reasons, it is recommended that a soil-specific calibration is undertaken prior to installation, using the number of attachments and cable lengths to be used in the field. In addition, as it will be shown later, the automated travel time analysis largely overestimated the values of K_a for high plasticity soils due to their high conductivity and the strong attenuation caused by the addition of multiplexers. It is therefore recommended that the cable length is kept to a minimum when using multiple levels of multiplexers.

Cross-Validation

The accuracy of the currently accepted ASTM method described by Jung et al. (2013a) and the proposed new method using Eq. (7) instead of Eq. (4) was tested by comparing the reference ρ_d and reference w against the corresponding values measured by TDR, as shown in Fig. 8. The 1:1 line indicates perfect agreement, and the envelopes show the boundaries corresponding to $\pm 5\%$ and $\pm 2\%$ error in the measurement of ρ_d and w, respectively. Importantly, it is noticeable that Eq. (7) provided a significant improvement in the estimation of both ρ_d and w for all the soils tested, with and without multiplexers. Although these results give an indication of the performance of the methods, they only describe their fitting power since they were tested against the same data used to develop the relationships. Hence, to verify the robustness of both steps of the calibration a k-fold cross-validation procedure was applied to the data. This procedure consists of splitting the original data set into two subsets and using only one subset to build the model, one for both steps of the calibration, and testing the quality of the fitting on the second subset. This procedure allows the predictive power of the model to be estimated. In other words, it shows how well the model will likely cope with new independent data not used for developing the model. Although this method provides better insights to the robustness of the model, it can be sensitive to the way the original dataset is split. In order to reduce bias toward the selection of specific data points, the original data set can be split randomly and the procedure repeated a number of times (i.e., k-times). In this study, a 10-fold cross-validation was used. As a result, 10 different models were created using different subsets for each soil and tested against the remaining data points for each

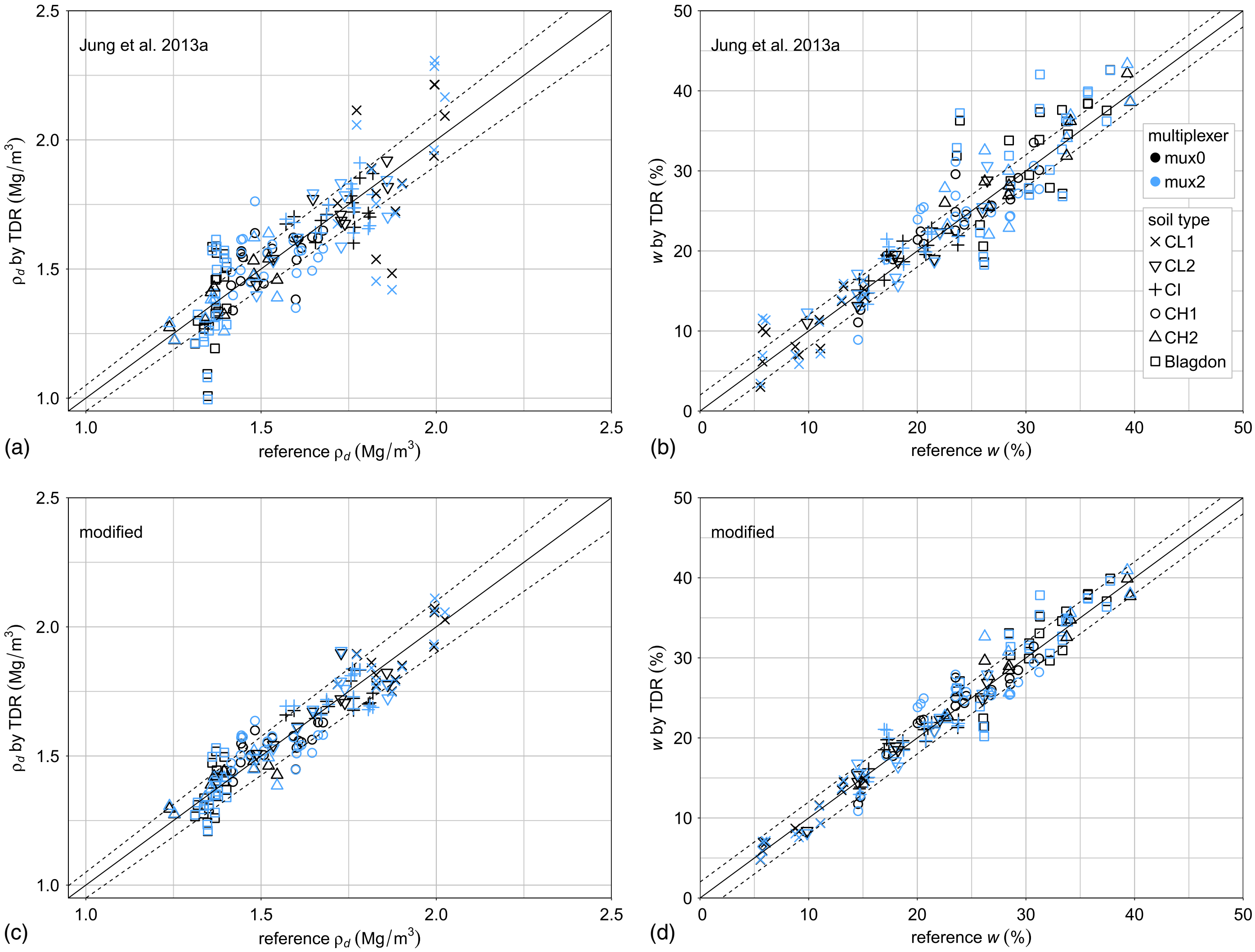

Fig. 8. (a and b) Overall accuracy of the Jung et al. (2013a) method; (c and d) the proposed new method

split. Due to the relatively small number of data and due to the nature of the compaction test, a completely random selection of data points was not deemed appropriate. In fact, a compaction curve should contain a minimum of five points covering a range of water contents and must have at least two points before and after the optimum moisture content (BSI 1999a). Hence, the original data set was first split in five subgroups using the gravimetric water content quantiles corresponding to the probabilities of 0.2, 0.4, 0.6, 0.8, and 1.0. For each of these subgroups, one data point was selected at random. This resulted in the selection of five random points for each soil covering the entire range of water contents tested that were subsequently used for building the models for Step 1 and Step 2 of the calibration. As mentioned earlier, the procedure was repeated 10 times, and the average coefficient of determination (R^2) for both steps of the calibration, the average root mean squared error (RMSE) and the average mean absolute error (MAE) were used to compare the models. Table 3 presents the results of this analysis showing the predictive power of the models built with only five data points (predictive evaluation statistics) and the corresponding quality of fitting obtained using all the available data points (fitting evaluation statistics). The first step of the calibration was common to both methods, and the high R^2 calculated in fitting and in prediction indicated the very good performance of Eq. (3). As expected, the R^2 calculated in prediction using fewer data points was smaller than the R^2 calculated using all available data but remained high. Table 3 also confirmed that Eq. (7) (i.e., the modified model) yielded better accuracy than Eq. (4) (Jung et al. 2013a), with a higher R^2 and a lower MAE and RMSE, both in fitting and particularly in prediction. On average, the new method reduced the MAE associated with ρ_d by $0.037\ \mathrm{Mg/m^3}$ in fitting and $0.048\ \mathrm{Mg/m^3}$ in prediction, and the MAE associated with w by 0.94% in fitting and 1.27% in prediction. The improvement was more significant when using multiplexers, with a MAE reduction of $0.045\ \mathrm{Mg/m^3}$ and 1.06% in fitting, and $0.056\ \mathrm{Mg/m^3}$ and 1.56% in prediction, for ρ_d and w, respectively. It is, however, apparent that both methods exhibited significant lower R^2 and higher MAE and RMSE if only five data points were used to develop Step 2 of the calibration. This is due to the nonlinear behavior of both relationships, making them more sensitive to the number of data points used. To develop a robust calibration and obtain better accuracy, it is therefore advisable to use more than five data points covering the entire range of the expected water contents.

Effect of Temperature and Compactive Effort

For the calibration to be accurate, the parameters measured by TDR must be corrected for temperature (Jung et al. 2013b), particularly if it is substantially different from the temperature used in the

Table 3. Summary of the Fitting and Predictive Power of the Analyzed Models

Evaluation statistics	Model	mux level	R^2 step1	R^2 step2	MAE ρ_d (Mg/m^3)	MAE w (%)	RMSE ρ_d (Mg/m^3)	RMSE w (%)
Fitting	Jung et al. (2013a)	mux0 and mux2	0.994	0.951	0.096	2.385	0.447	11.255
Fitting	Modified	mux0 and mux2	0.994	0.982	0.059	1.448	0.273	6.833
Prediction	Jung et al. (2013a)	mux0 and mux2	0.986	0.818	0.118	2.971	0.474	12.371
Prediction	Modified	mux0 and mux2	0.986	0.960	0.070	1.698	0.295	6.842
Fitting	Jung et al. (2013a)	mux0	0.995	0.959	0.085	1.980	0.396	9.480
Fitting	Modified	mux0	0.995	0.984	0.054	1.165	0.253	5.580
Prediction	Jung et al. (2013a)	mux0	0.991	0.913	0.101	2.388	0.403	9.538
Prediction	Modified	mux0	0.991	0.966	0.062	1.403	0.248	5.646
Fitting	Jung et al. (2013a)	mux2	0.992	0.942	0.108	2.790	0.498	13.030
Fitting	Modified	mux2	0.992	0.980	0.063	1.732	0.293	8.085
Prediction	Jung et al. (2013a)	mux2	0.982	0.722	0.135	3.555	0.546	15.204
Prediction	Modified	mux2	0.982	0.953	0.079	1.993	0.342	8.039

laboratory during calibration (usually 20 or 25°C). The temperature effect on the measured K_a has been described by other authors and is not a simple relationship (Or and Wraith 1999; Wraith and Or 1999; Logsdon 2000; Skierucha 2009). In water, K_a exhibits an inverse relationship with temperature (Weast 1972). However, in soils with a high specific surface area, the release of bound water with increasing temperature generates a competing positive relationship. As a result, it is difficult to predict the K_a dependence on temperature for a given soil type. It is worth noting that the change in K_a due to temperature is less important compared to, for example, electrical conductivity (Wraith and Or 1999). The relationship of V_1 and V_f with temperature is more straightforward, and it was found to be linear, positive for V_1 and negative for V_f. Attempts were also made to develop temperature corrections directly based on V_r. However, it was found that the individual corrections for V_1 and V_f yielded more accurate results and were therefore preferred. Fig. 9 shows the results of a set of experiments conducted in an incubator with the soil samples tested between 5 and 25°C (see section "Experimental Procedure" for more details). The temperature corrections for V_1, V_f, and K_a were determined empirically for each soil type, and a separate correction was used for the two different TDR setups, with and without multiplexers. As shown in Fig. 9, the relationships were strongly linear for V_1 and V_f and were less pronounced for K_a. The relationship between temperature and K_a was positive, indicating that the release of bound water was dominant in the soils studied (Or and Wraith 1990). The TDR parameters were also corrected using the equations proposed by Jung et al. (2013b). These equations produced more variable results with slightly larger errors, and therefore, it was deemed more appropriate to run the comparison between the two methods using the empirical temperature corrections developed for each soil type. The choice of the temperature corrections used, either the ones proposed by Jung et al. (2013b) or the soil-specific empirical corrections, did not affect the general conclusions of this analysis. The empirical temperature corrections took the form of Eq. (10)

$$Y_{\mathrm{cor}} = m \times (T_{\mathrm{ref}} - T_{\mathrm{meas}}) + Y_{\mathrm{meas}} \tag{10}$$

where Y = parameter to be corrected; T = temperature (°C); and m = slope obtained empirically from the tests in the incubator (the subscripts *cor*, *ref*, and *meas* stand for corrected, reference, and measured, respectively). For this study, 20°C was used as the reference temperature because the majority of the calibration tests were conducted at this temperature. It is interesting to note that the slopes used for the correction were only slightly different for the different soil types. All the soils studied were fine-grained, and this supports the approach by Jung et al. (2013b) of using the same correction for similar soils, i.e., one for fine-grained soils and one for coarse-grained soils. Table 4 shows the slopes used for correction calculated for each of the soils studied, with and without multiplexers. Fig. 9 also shows the effect of multiplexers on the TDR parameters. Both V_1 and V_f were reduced due to attenuation when using multiplexers, with V_1 being most affected. The measurement of K_a on the Blagdon and CH1 soils were strongly affected by multiplexers due to their high conductivity and subsequent larger uncertainty associated with the identification of the end reflection point. Closer inspection of the waveforms for these soils indicated that K_a was largely overestimated when using multiplexers, sometimes by over 5 units. Manual travel time analysis (i.e., manually applying tangents) could potentially reduce this error but was not attempted in this study as it is not practical for field monitoring applications, when many measurements are normally taken automatically. Modification of the automated method used in the travel time analysis (i.e., improved automatic application of tangents) was outside the remit of this research; therefore, a correction was not attempted. For these soils, higher errors are therefore expected when using multiplexers, and it is suggested that additional research into automated analysis of TDR waveforms collected via multiplexers would be beneficial. The soil samples tested at a range of temperatures were prepared at water contents close to the optimum corresponding to the standard compaction method. The lighter and heavier compacted samples were also prepared at approximately the same water content, but because of the different compaction energy applied, they had different ρ_d values. The results shown in Fig. 9 indicate that the relationships between the TDR parameters and temperature remained approximately constant with varying ρ_d, suggesting that the corrections are robust. By varying both temperature and compactive effort, the data set collected in this experiment was well suited for an independent and strong validation of the calibration for ρ_d and w. Fig. 10 shows the mean, maximum, and minimum errors for both ρ_d [Fig. 10(a)] and w [Fig. 10(b)], with and without multiplexers and for each compactive effort using the Jung et al. (2013a) methodology and the proposed new method after applying the soil-specific temperature correction on V_1, V_f, and K_a using Eq. (10). It can be seen that the mean and maximum errors were reduced by the new method in almost all instances and both were substantially reduced when using multiplexers. The mean absolute error without multiplexers considering all the soils was reduced, on average, by the new method by 0.040 Mg/m^3 and 0.95% for ρ_d and w, respectively. With the arrangement using multiplexers, the improvement was more significant with an error reduction of 0.069 Mg/m^3 and 2.25% for ρ_d and w, respectively. This improvement was consistent

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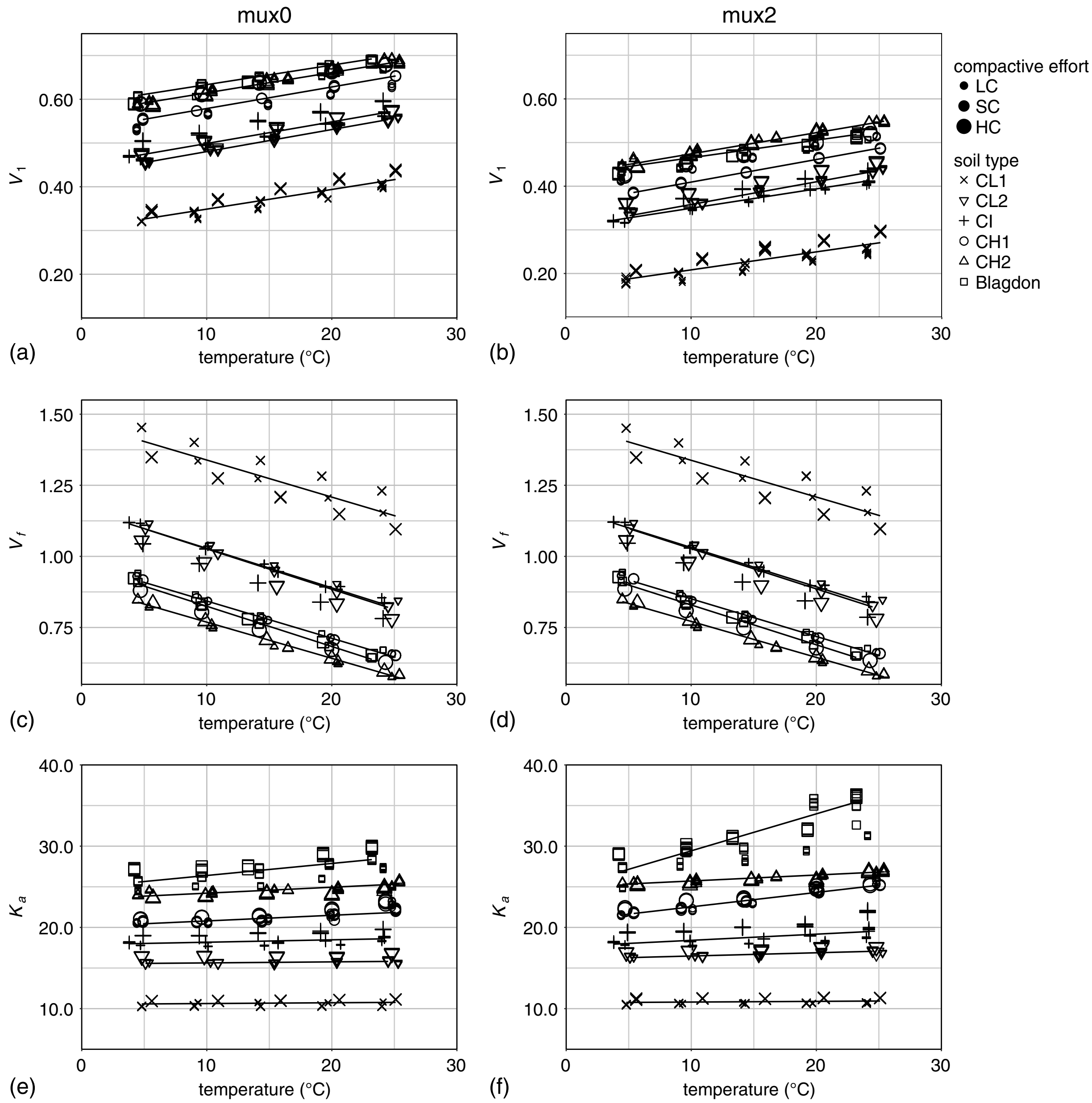

Fig. 9. Relationships between the TDR parameters and temperature used to develop the corresponding temperature corrections: (a, c, and e) calculated without multiplexers (mux0); (b, d, and f) calculated with two levels of multiplexers (mux2)

Table 4. Temperature Correction Coefficients (i.e., Slopes) Calculated without Multiplexers (mux0) and with Two Levels of Multiplexers (mux2)

Soil type	m (K_a)	m (V_1)	m (V_f)
CL1_mux0	0.009736	0.004377	−0.011621
CL2_mux0	0.005173	0.005046	−0.014187
CI_mux0	0.028721	0.004945	−0.013885
CH1_mux0	0.093108	0.004930	−0.013112
CH2_mux0	0.054453	0.004647	−0.012727
Blagdon_mux0	0.141762	0.004460	−0.014155
CL1_mux2	0.008550	0.003920	−0.011467
CL2_mux2	0.031354	0.005206	−0.014143
CI_mux2	0.077199	0.004443	−0.013800
CH1_mux2	0.177618	0.005183	−0.013230
CH2_mux2	0.067559	0.004860	−0.012654
Blagdon_mux2	0.360400	0.004035	−0.014009

with the values obtained from the cross-validation analysis. With a few exceptions, the measurements using the new method were within an error of 0.2 Mg/m^3 for ρ_d and 3% for w. As can be seen from Fig. 10, both methods generally remained relatively unaffected by the compactive effort. Fig. 11 shows the results of the experiments conducted at a range of water contents using the CI soil mixture and a TDR probe buried horizontally (see section “Experimental Procedure” for more details). As mentioned earlier, the CI soil was selected because of its intermediate plasticity characteristics according to Fig. 2. As stated previously, both the Jung et al. (2013a) method and the new method were compared after applying a temperature correction to the data using Eq. (10). These results further confirm the better performance of the modified method, with significant improved accuracy and reduced multiplexer effect. Importantly, the variability in the measurements was also reduced compared to the Jung et al. (2013a) method.

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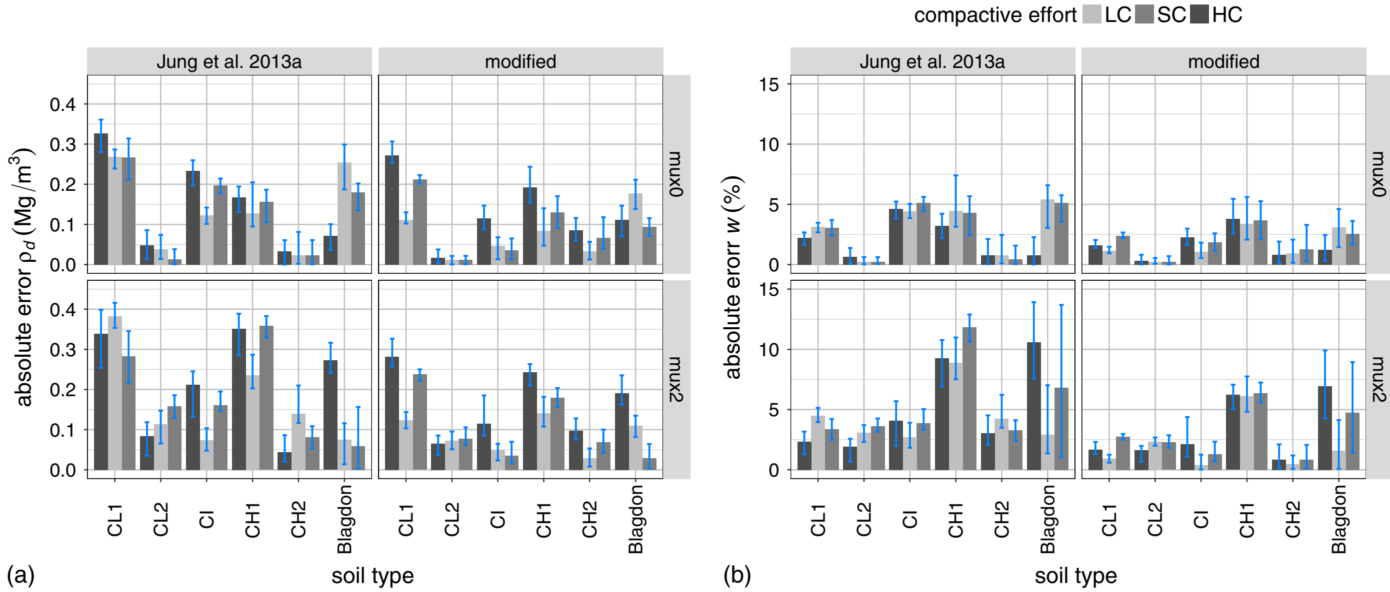

Fig. 10. Summary of the errors for (a) ρ_d and (b) w after applying temperature correction obtained using the Jung et al. (2013a) method and the proposed new method on a set of independent tests conducted at a range of temperatures and compactive efforts [note that Eq. (10) was used for the temperature correction on both methods]

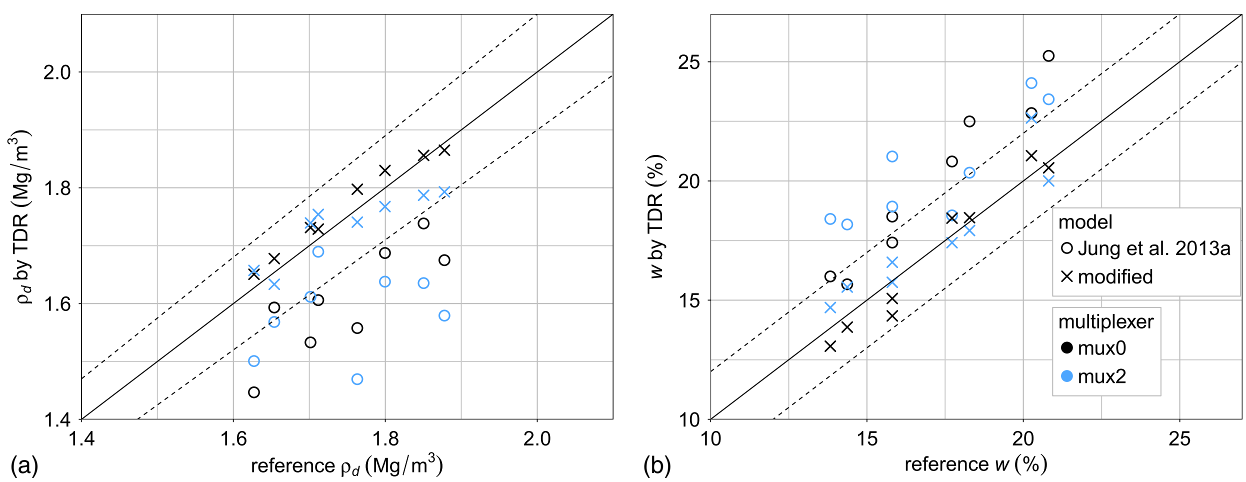

Fig. 11. Accuracy of (a) ρ_d and (b) w resulting from an independent test conducted on the CI soil with the TDR probe buried horizontally and the soil compacted in layers using a Kango vibratory hammer

It is worth noting that in field monitoring, precise measurements with a systematic error are usually preferable rather than accurate but variable measurements.

Further Considerations

In the field, TDR probes are often buried horizontally or at an angle. The impact of different probe orientations on the methods described was not the primary aim of this study and remains a matter for future research. In addition, further research is required to extend the current study using field experiments and tests on coarse-grained soils for the proposed new method to be fully accepted. The impact of varying pore water conductivity should also be examined in detail to verify the robustness of the method. Nonetheless, this study has demonstrated promising developments on the use of off-the-shelf TDR for measuring soil properties and demonstrated the versatility of this technology. A wide range of soil parameters can be calculated or estimated from the knowledge of ρ_d and w, including the degree of saturation and potentially the shear strength. Therefore, the potential applications are many, including but not limited to, compaction quality control, slope stability, excavation stability, and infrastructure monitoring (e.g., embankments, the ground below roads and around buried utility assets). The data collected in this study suggests that the proposed new method is an improvement over the currently accepted method for measuring the soil ρ_d and w. However, the collection of a larger data set and independent validation tests will ultimately verify the usefulness of the new proposed method.

Conclusions

The aim of this investigation was to determine if TDR could be used in long-term geotechnical asset condition monitoring. For this to be suitable, the probes would have to be relatively inexpensive and survive burial without compromising the reinstatement of the ground (presumably via compaction). In addition, it is envisaged that multiple probes would require burial and, to ensure the system is cost effective, multiplexers would be required. It was apparent from the outcomes of this study (investigating a range of fine-grained soils using commercially available three-rod TDR probes and, in certain tests, two levels of multiplexers) that the method reported in ASTM-D6780/D6780M (specifically, the second step of the method) did not provide very consistent results and was affected by the addition of the multiplexers. Thus, if TDR is to be used in long-term geotechnical asset condition monitoring, the TDR methods for determining both water content and dry density would have to be modified. A new modified relationship has been proposed that replaces Step 2 of the calibration in ASTM-D6780/D6780M. This yields improved precision and accuracy and is less affected by the use of multiplexers. The typical accuracy for the investigated soils was to within an error of $\pm 5\%$ for ρ_d, and $\pm 2\%$ for w, both with and without multiplexers, although occasionally larger errors were measured, but these were still consistently smaller than the errors produced by ASTM-D6780/D6780M. It has been confirmed that the TDR parameters must be corrected for temperature to improve the accuracy; therefore, temperature sensors should be employed alongside the TDR probes when attempting to monitor the relative condition of geotechnical assets with TDR. The TDR probes and multiplexers used in this study are commercially available and well suited to field monitoring, thus it is believed that the proposed relationship could extend the potential uses of TDR to geotechnical applications for monitoring of geotechnical assets (such as earth dams, embankments, and slopes), and as such has provided a significant avenue for further exploitation of this technique.

Acknowledgments

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